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Silicon Lightweight Mirrors for Ultraviolet and Extreme Ultraviolet Imaging Mirrors Results of Phase I NASA SBIR

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Introduction

- Subtopic 01-S1.06 Imaging Mirrors for UV and EUV
  - Waveband: UV (300-400 nm), EUV (20-300 nm)
  - Diameter: 0.5-2.4 meters,
  - Areal Density: <20 kg/m^2
  - Surface Figure: 0.02-0.005 waves rms @633nm
  - Surface Finish: 0.5-1 nm rms
  - Midfrequency Error: 1.0-2.5 nm rms
- Achievements prior to Phase I (mirrors for Visible to IR)
  - Flat and Spherical Silicon Lightweight Mirrors (SLMS)
  - Cryo-stable to 40K
  - Areal Density: <15 kg/m^2
  - Surface Figure: 0.033 waves rms @ 633nm
  - Surface Finish: 0.5 nm rms
- Phase I Objective: Improve surface figure and finish of SLMS to meet requirements of UV and EUV optics
- Produced a 12.5 cm diameter, spherical UV Demonstrator Mirror suitable for cryo-testing in the C/SiC mounts built for NASA GSFC

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History of NASA Support for SLMS

- **Schafer has produced SLMS on three previous NASA sole source (SS) contracts:**
  - **Marshall Space Flight Center Purchase Order #H-28240-D, Schafer Proposal # P-98L-57, *Design, Fabrication and Cryogenic Test of a Small Ultra-light Silicon Foam-Backed Single Crystal Silicon Mirror*, performed for Dr. Edward "Sandy" Montgomery NASA MSFC**
  - **Goddard Space Flight Center Purchase Order # S-32479-G, Schafer Proposal # P-99L-267, *Silicon Lightweight Demonstration Mirror*, performed for Dr. David Content NASA GSFC**
  - **NSI Prime Contract # NAS5-32537, ManTech Systems Engineering Corporation Purchase Order # 20000962, Schafer Proposal # P-00L-217, *Offner Relay System*, performed for Dr. David Content NASA GSFC**

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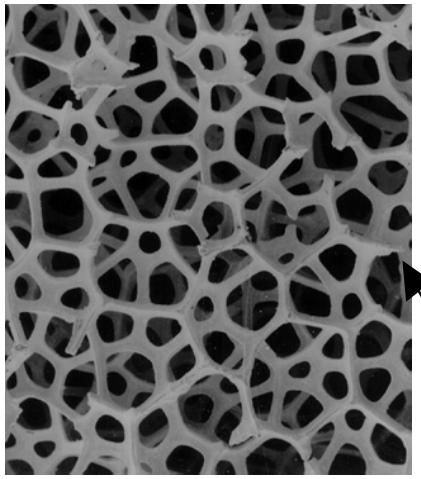
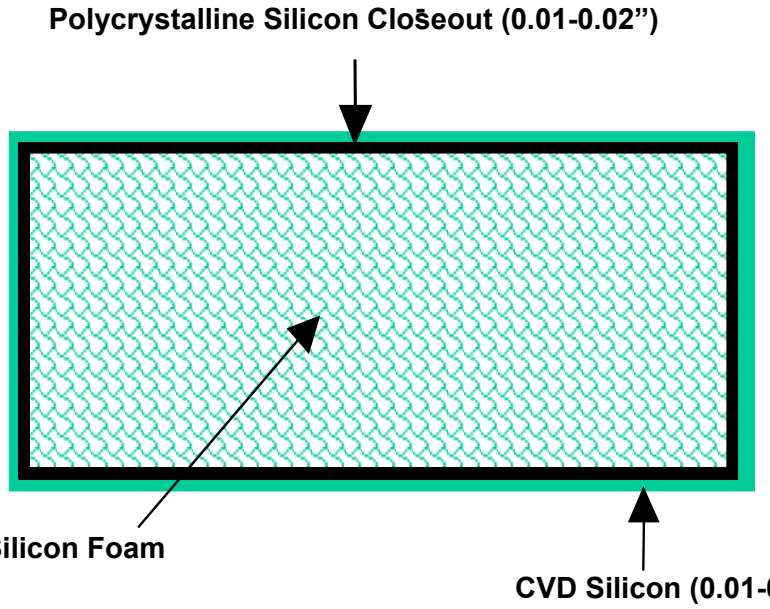
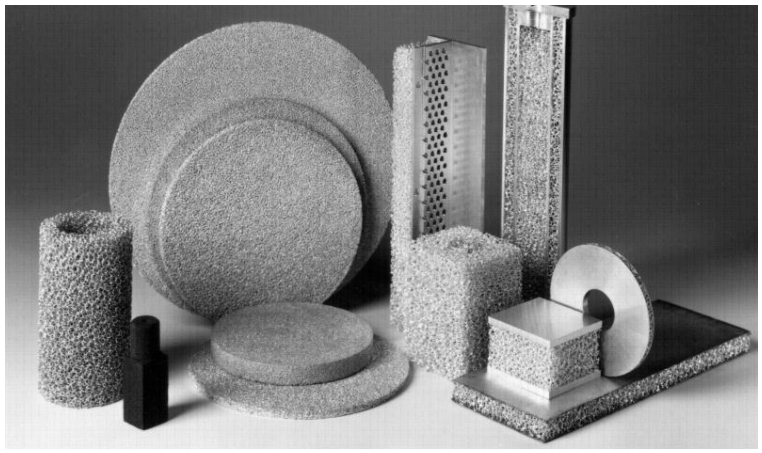
SLMS Composite Structure



Continuous pores
65-100 pore per inch





Foam can be CNC machined to virtually any shape

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SLMS Manufacturing Process

- Typical manufacturing time for flats and spheres is 10-12 weeks
- Polishing times for aspheres typically 3-6 months
- Current infrastructure supports up to 32 cm diameter
- Metal or dielectric coatings are readily applied

Silicon Foam

Polycrystalline Silicon Close-out on 5-inch sphere

Polished CVD Silicon

- **Very Low Absorption coating applied to SLMS for HEL applications**

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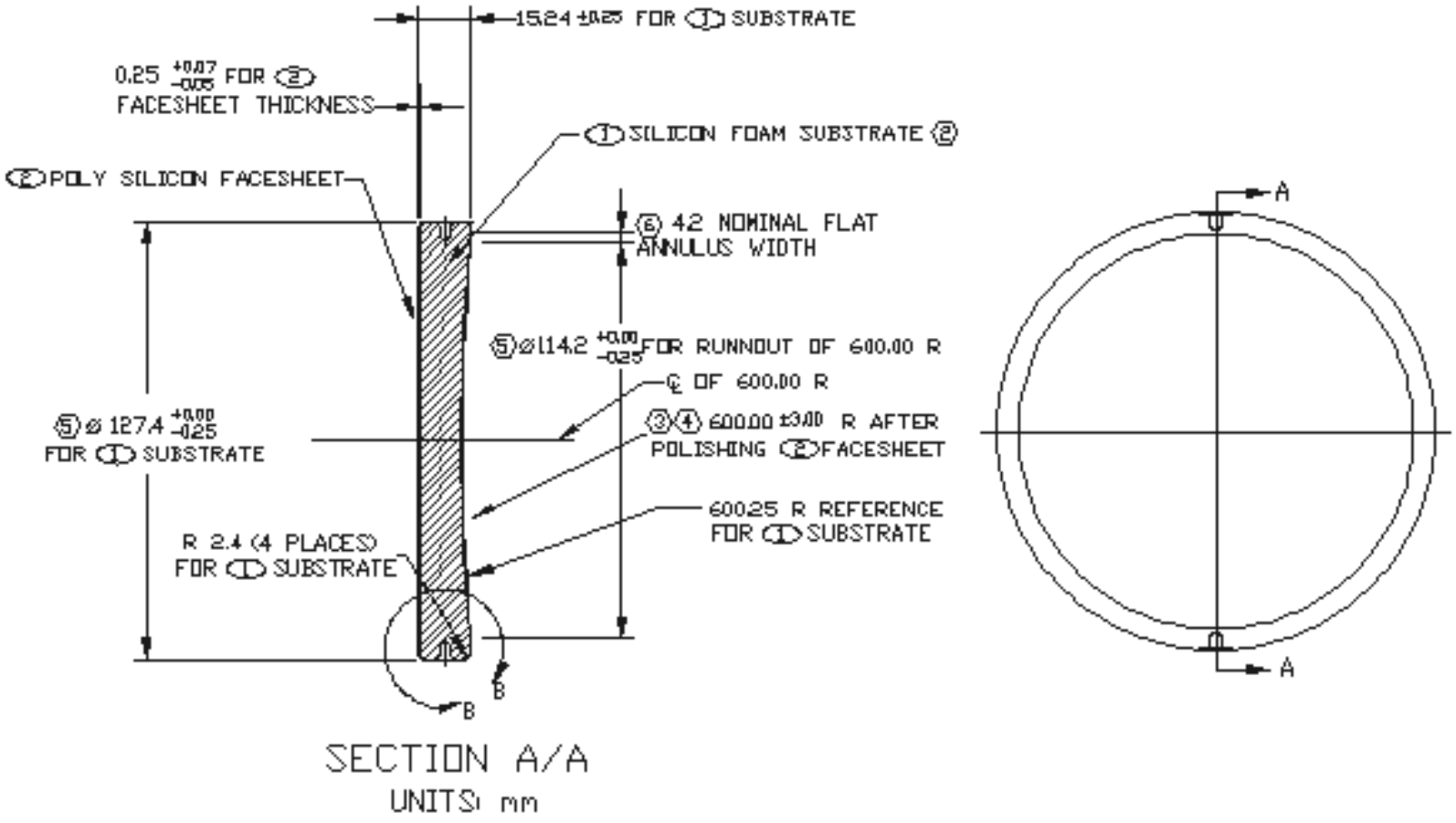
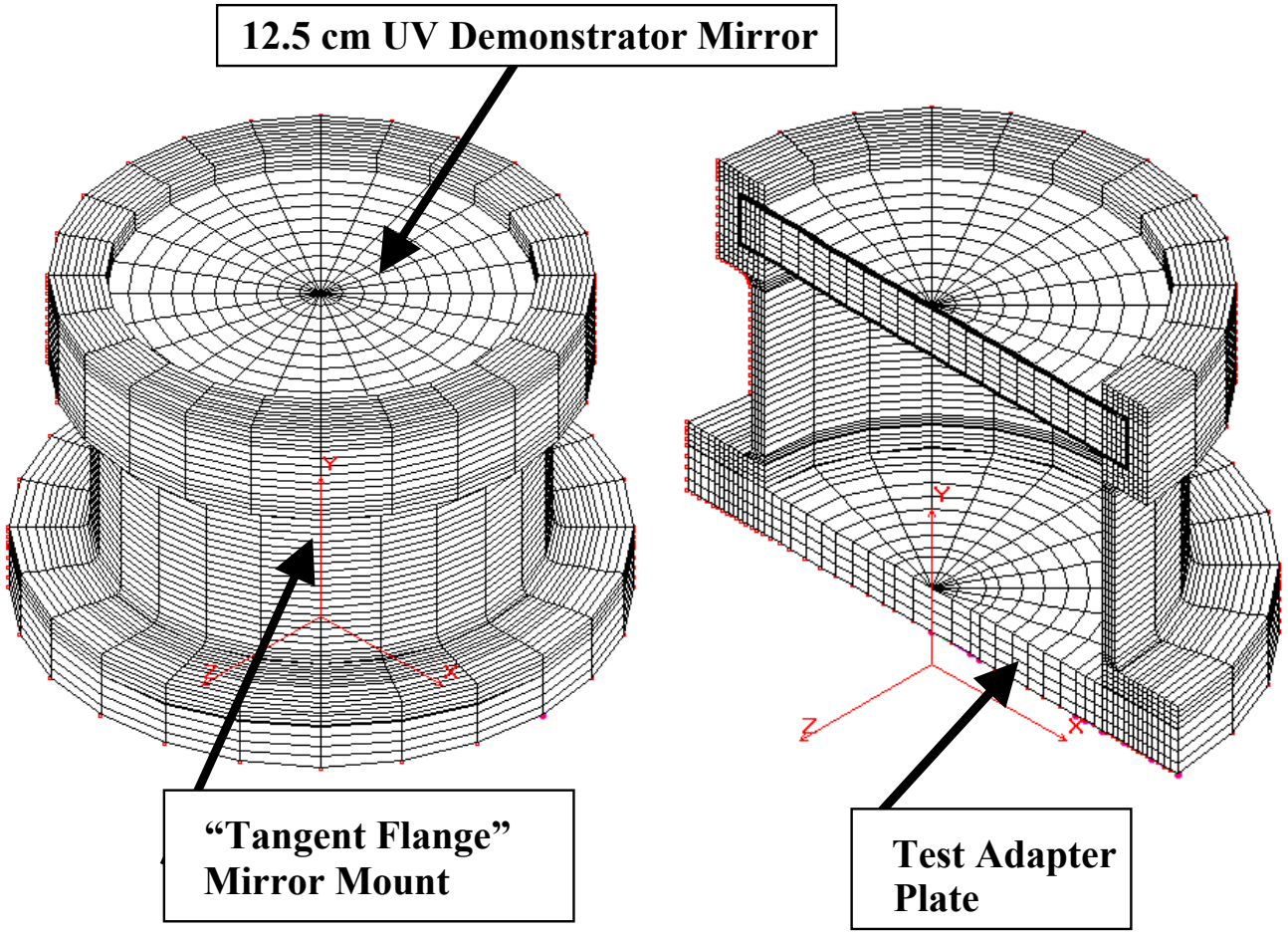
Schematic of UV Demonstrator Mirror

- **UV Demonstrator Mirror clear aperture (CA) is the central 10.5 cm dia.**



Structural Analysis

- **Modeled kinematic and Schafer "tangent flange" mounts**
  - **3:2:1 kinematic mount has six independent reactions**
  - **Tangent flange provides uniform support around the periphery near the O.D**
  - **Tangent flange mount fabricated using CTE matched C/SiC material**



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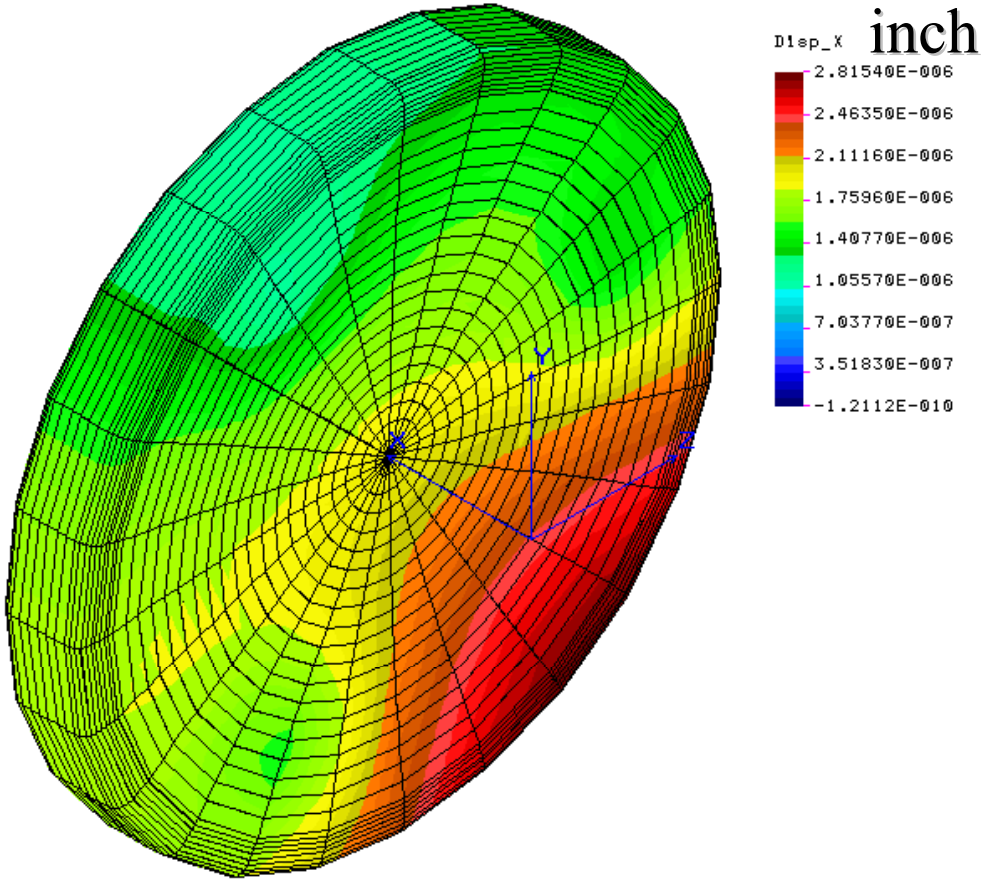
1-G Load with Kinematic Mount

- The maximum sag over 100% CA is 2.5 μ-inch (63.5 nm)
- Surface distortion is asymmetrical



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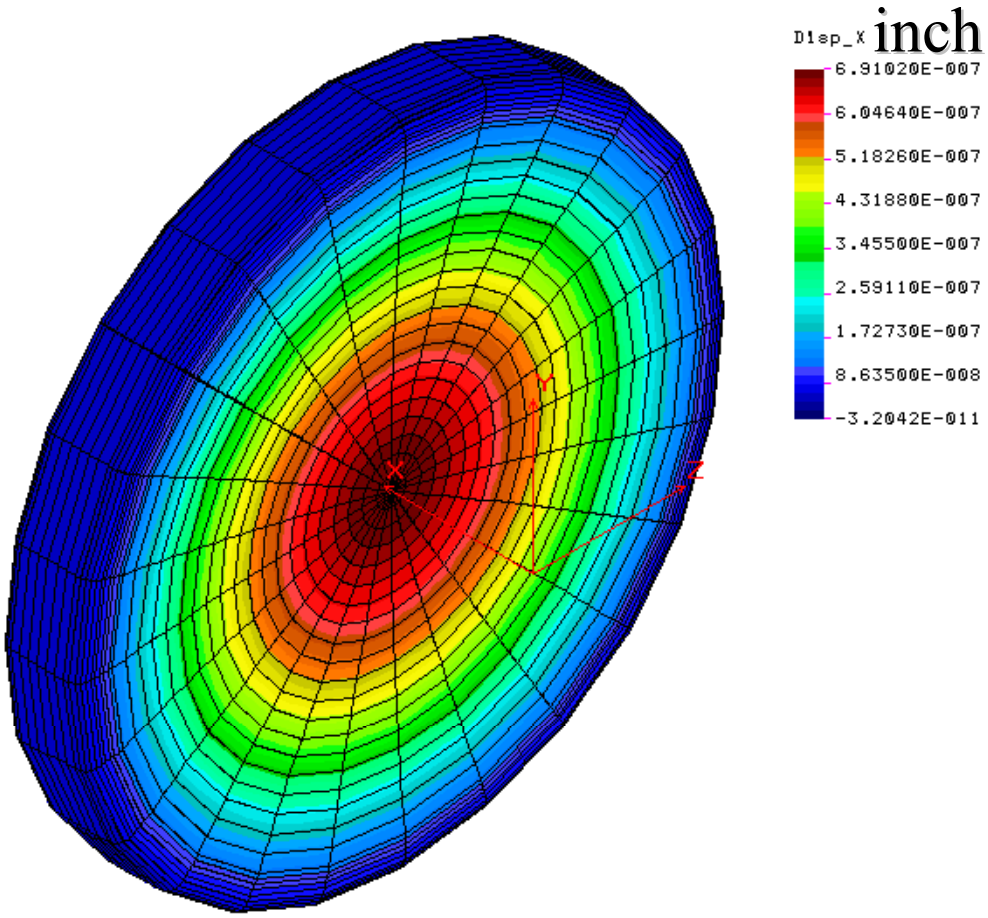
1-G Normal Load with Tangent Mount

- The maximum sag over 100% CA is 0.58 μ-inch (14.7 nm)
- Surface distortion is a symmetrical, focus type aberration



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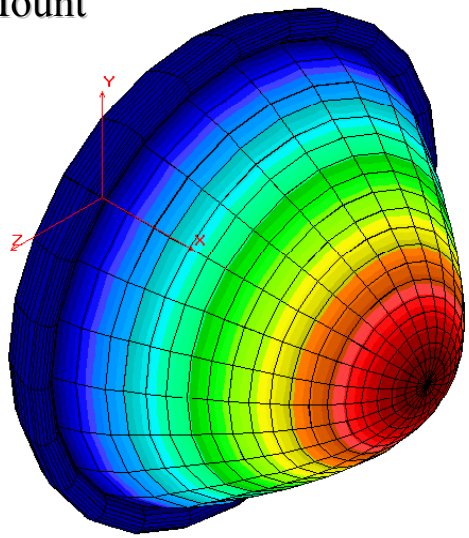
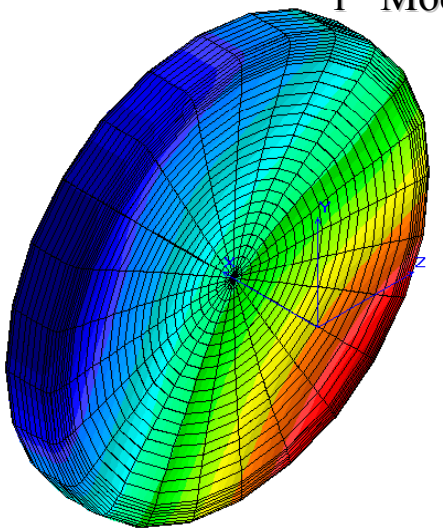
SLMS Have High Stiffness

Tangent Flange Mount				Kinematic Mount			
Mode	Frequency (Rad/sec)	Frequency (hertz)	Period (seconds)	Mode	Frequency (Rad/sec)	Frequency (hertz)	Period (seconds)
1	31709.0	5046.7	1.9815E-04	1	11319.90	1801.62	5.5506E-04
2	53648.0	8538.4	1.1712E-04	2	13818.10	2199.22	4.5471E-04
3	53648.0	8538.4	1.1712E-04	3	15541.20	2473.46	4.0429E-04
4	71462.4	11373.6	8.7923E-05	4	18815.20	2994.53	3.3394E-04
5	71462.4	11373.6	8.7923E-05	5	25143.40	4001.70	2.4989E-04
6	71954.1	11451.8	8.7322E-05	6	31887.10	5074.99	1.9705E-04
7	71954.1	11451.8	8.7322E-05	7	35979.30	5726.28	1.7463E-04
8	77428.4	12323.1	8.1148E-05	8	36672.50	5836.60	1.7133E-04
9	89810.2	14293.7	6.9961E-05	9	42046.60	6691.92	1.4943E-04
10	98509.4	15678.3	6.3783E-05	10	60305.50	9597.92	1.0419E-04

1st Mode with Tangent Mount is 5047 Hz



1st Mode with Kinematic Mount is 1801 Hz



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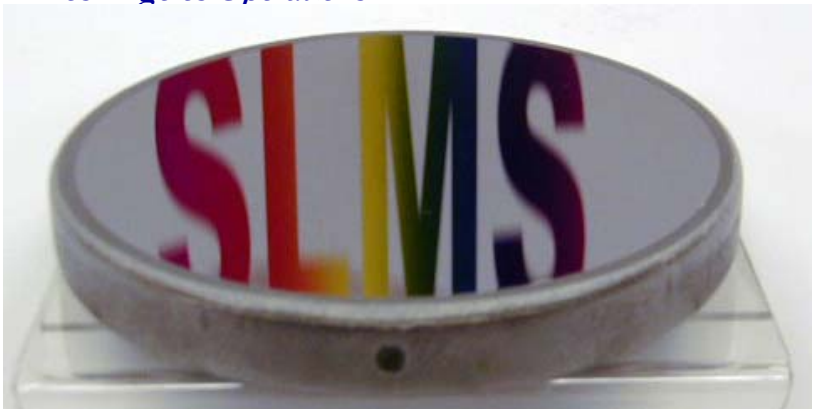
UV Demonstrator Mirror Results



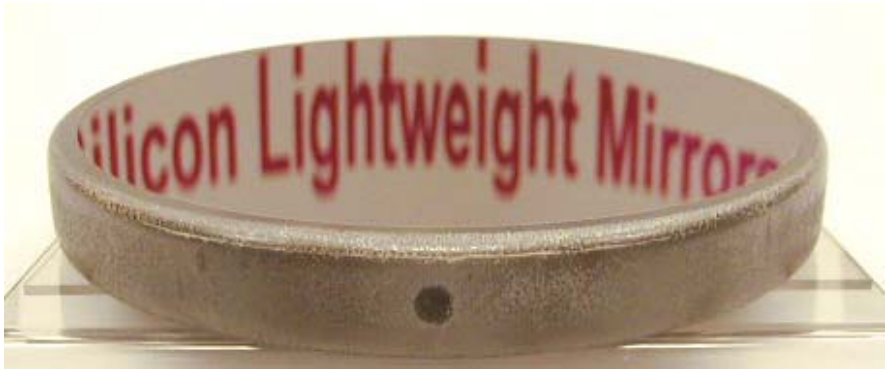


Figure of Merit	Specified Value	Results Achieved	Achievable
Areal Density, kg/m^2	<20	**9.8**	6
Surface Figure at 80% CA, waves rms @633 nm	0.02	0.021	0.005
Surface Figure at 95% CA, waves rms @633 nm	N/A	0.027	0.010
Surface Roughness, Å rms	10	**4**	1
Radius of Curvature	600 mm ± 0.5%	**598.559 ± 0.005 mm 2-σ**	
Surface Quality (Scratch/Dig)	60/40	**20/20**	10/5

- **Achieved or Exceeded All Specifications**
- **Mirror was Lapped and Polished for only 10 Days**

Supporting Data

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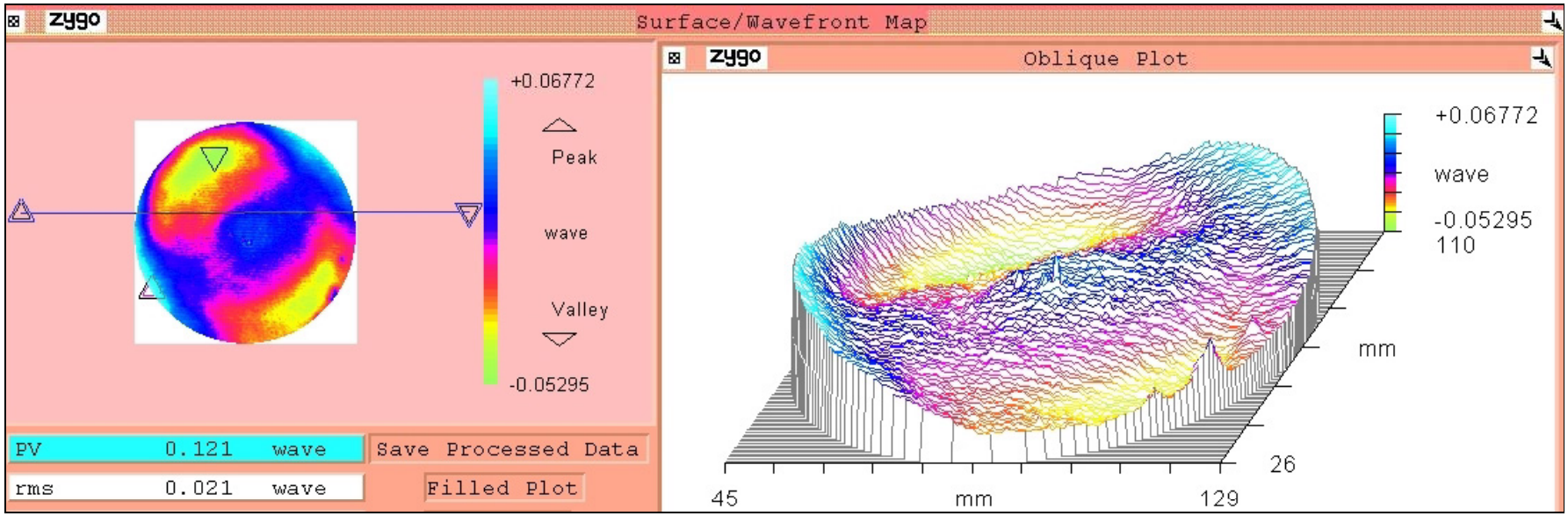
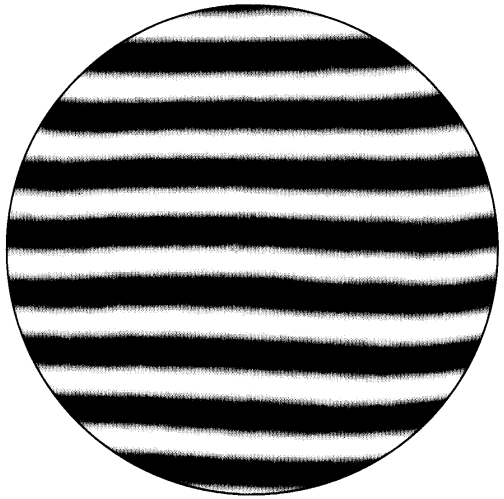
Surface Figure Over 80% CA





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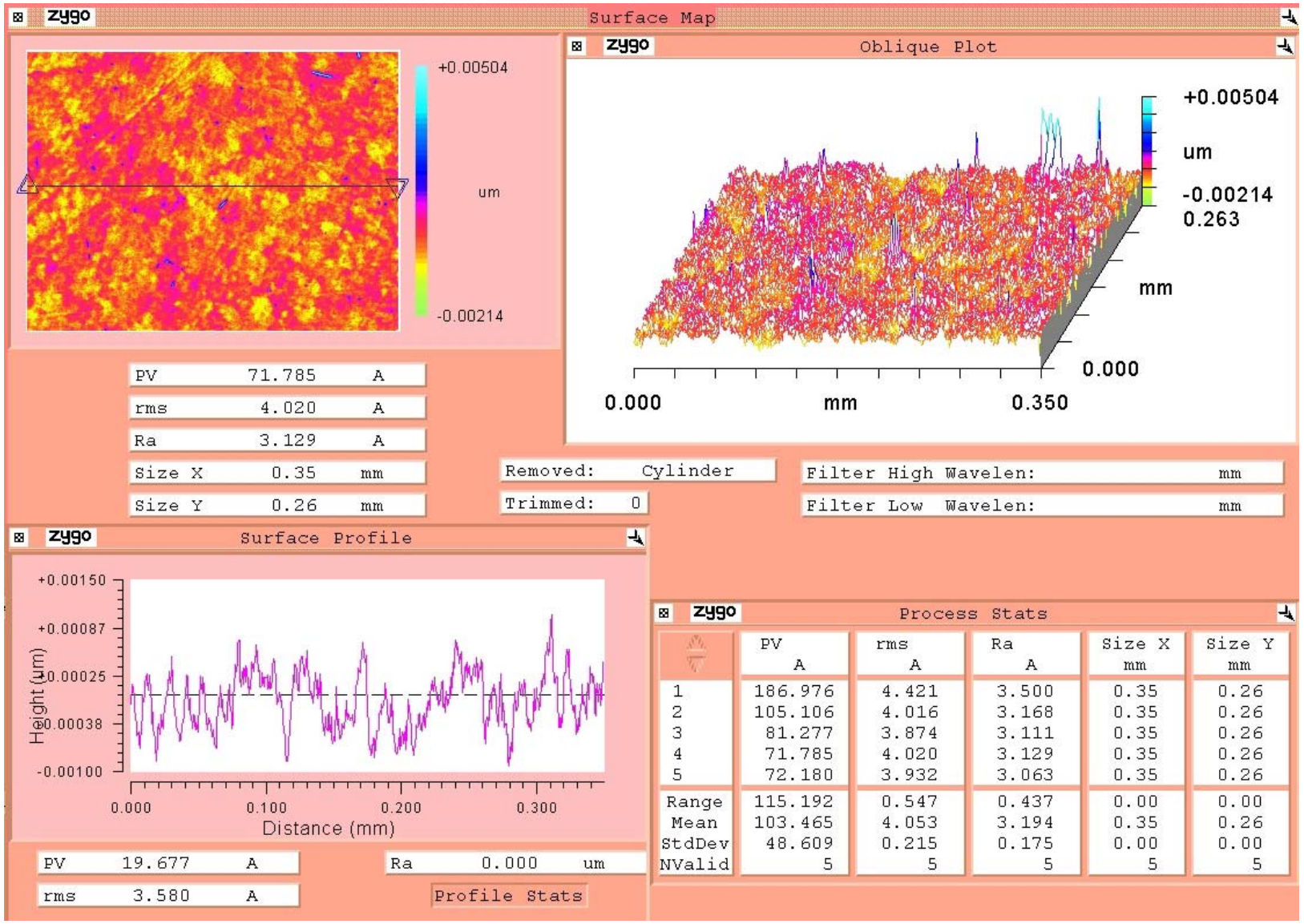
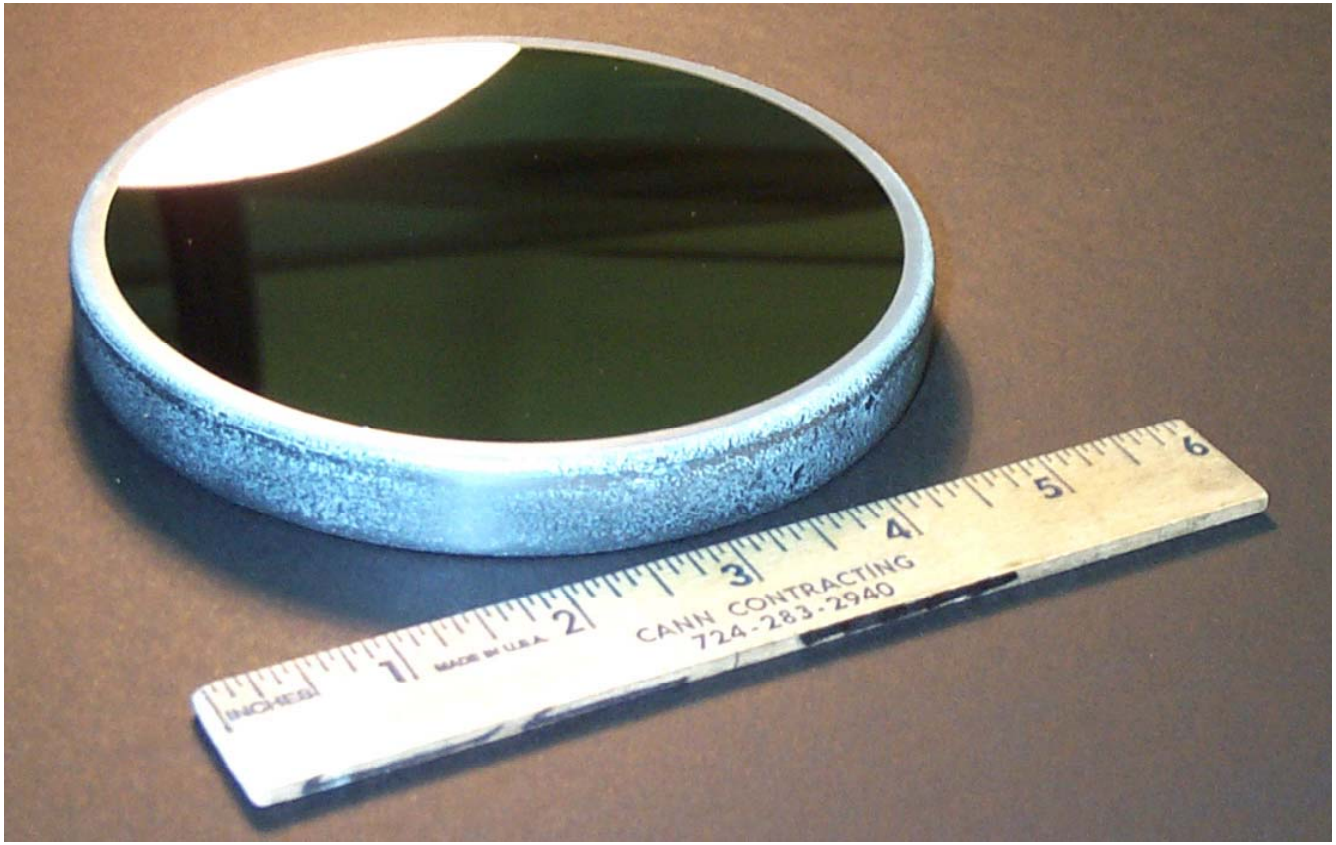
Surface Finish Over 95% CA



	PV A	rms A	Ra A	Size X mm	Size Y mm
1	186.976	4.421	3.500	0.35	0.26
2	105.106	4.016	3.168	0.35	0.26
3	81.277	3.874	3.111	0.35	0.26
4	71.785	4.020	3.129	0.35	0.26
5	72.180	3.932	3.063	0.35	0.26
Range	115.192	0.547	0.437	0.00	0.00
Mean	103.465	4.053	3.194	0.35	0.26
StdDev	48.609	0.215	0.175	0.00	0.00
NValid	5	5	5	5	5

Surface Quality Over 95% CA

- Surface Quality 20/20 Scratch/Dig



Commercialization Plan

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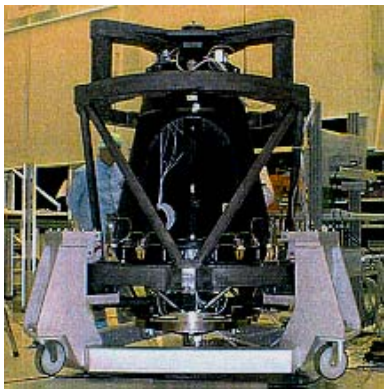
Business Objective and Products

- ***Objective***: **Become the leader in producing low cost, lightweight, athermal optical systems for commercial, government civilian and defense applications. Schafer products have significant cost, schedule and performance advantages over Beryllium, ULE, Zerodur and SiC products.**

- ***Products:*** **Using Schafer developed Silicon Lightweight Mirrors (SLMS) and complementary C/SiC mirror & structures technologies to manufacture optics, optical mounts and optical benches at the component, subsystem or system level of assembly/integration, for operation in ground, air and space environments, from the far infrared to extreme ultraviolet spectral regions, and over a wide range of temperatures.**



C/SiC Mounts and Optical Benches

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Technology Readiness Level Roadmap

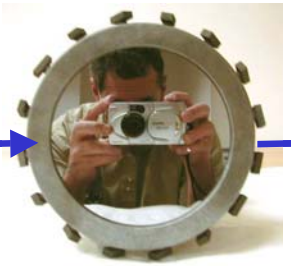
- **Silicon Lightweight Mirrors (SLMS) and complementary C/SiC mirror & structures currently at Technology Readiness Level 3.5 – 4.0**

CNC Shape
RVC Foam

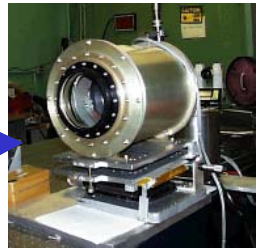
Silicon Foam
Substrate

Polycrystalline
Silicon Close-out

Polished SLMS
λ/50 rms HeNe, 4 Å rms

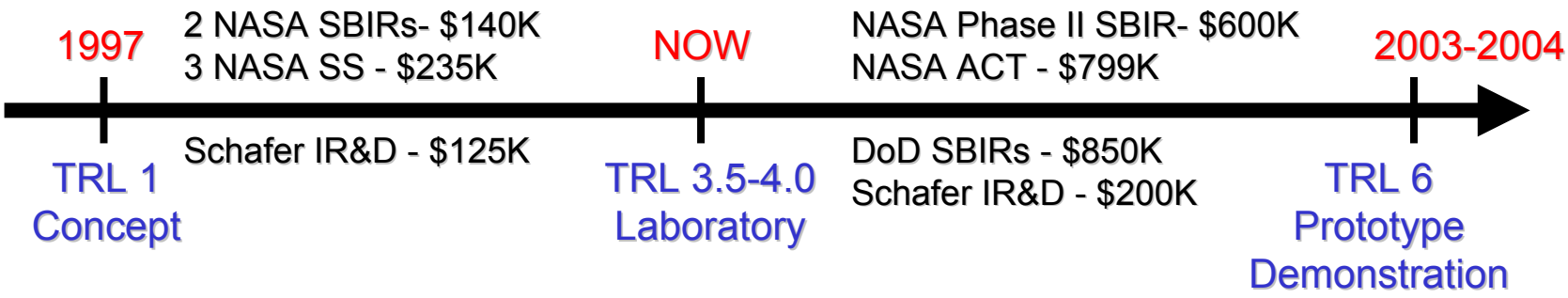


C/SiC Mount



NASA GSFC Dewar

- **Commercial System Houses and NASA Missions require ≥ TRL 6**



Summary

- The UV Demonstrator Mirror meets or exceeds all of the stated goals, thus we have proven the feasibility of the innovation. These results strongly justify the continuation of the Phase II program.

- SLMS technology will significantly impact and benefit a very broad set of future NASA Space Science Enterprise (e.g., Next Generation Space Telescope, Explorer Program) and Earth Science Enterprise missions. SLMS will provide a national benefit beyond NASA for DoD (Directed Energy, Imaging), DoC/NOAA (Remote Imaging) and commercial optical system houses.